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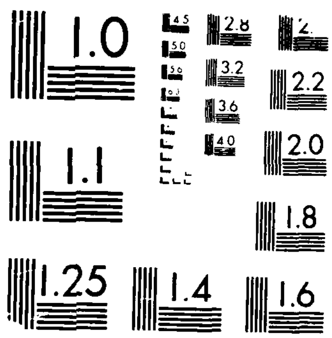

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Sound wave propagation in thin film carbon is investigated in the long wavelength approximation. Strain-free and stress-free boundary conditions lead to the same solution. The Rayleigh wave, with a small damping constant and with polarization perpendicular to the layer planes, has a small sound velocity. Since the long wavelength phonon energies associated with this wave are very small, these phonon are readily excited even at very low temperatures. Furthermore, these phonons strongly scatter carriers at low temperatures. Of particular interest for transport properties is the determination of the carrier relaxation time for very thin film thicknesses. These phonons are also responsible for the temperature dependence of the negative magnetoresistance of pregraphitic carbons at low temperatures.

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ELECTRON–RAYLEIGH WAVE INTERACTION IN THIN FILM CARBONS[1]

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ABSTRACT

Sound wave propagation in thin film carbon is investigated in the long wavelength approximation. Strain–free and stress–free boundary conditions lead to the same solution. The Rayleigh wave, with a small damping constant and with polarization along the c–axis, has a small sound velocity $v_R \sim 10^4$ cm/sec. Since the long wavelength phonon energies associated with this wave are very small ($\hbar\omega_q/k_0 \sim 1K$), these phonon are highly excited even at $T \leq 1K$; furthermore, these phonons strongly scatter carriers at low temperatures. Of particular interest for transport properties is the carrier relaxation time $\tau_R \sim 10^{-12}$ sec for thin film thicknesses $d < 100\text{Å}$. These phonons are also responsible for the temperature–dependent negative magnetoresistance of pregraphitic carbons at low temperatures.

SOUND WAVE PROPAGATION IN THIN FILM CARBONS

In the long wavelength approximation the lattice vibration of graphite is described by the following equations:

$$\begin{aligned}\frac{\partial u_x}{\partial t^2} &= v_\ell^2 \frac{\partial^2 u_x}{\partial x^2} + v_t^2 \frac{\partial^2 u_x}{\partial y^2} + v_\ell^2\left(\frac{1+\sigma}{2}\right)\frac{\partial^2 u_y}{\partial x \partial y} + \varsigma\left[\frac{\partial^2 u_x}{\partial z^2} + \frac{\partial^2 u_z}{\partial x \partial z}\right],\\ \frac{\partial^2 u_z}{\partial t^2} &= \varsigma\left[\frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2}\right] + v_z^2 \frac{\partial^2 u_z}{\partial z^2} + \varsigma\left[\frac{\partial^2 u_x}{\partial x \partial z} + \frac{\partial^2 u_y}{\partial y \partial z}\right],\end{aligned} \tag{1}$$

where $\vec{u} = (u_x, u_y, u_z)$ is a displacement vector and $\partial^2 u_y/\partial t^2$ is obtained by interchanging $x \leftrightarrow y$ in $\partial^2 u_x/\partial t^2$. Other quantities in Eq. 1 are:

$$\begin{aligned} v_\ell &= (C_{11}/\rho)^{\frac{1}{2}} = 2.10 \times 10^6 \text{cm/sec}, \;\; \rho = \text{density} = 2.26 \text{g/cm}^3,\\ v_t &= [(C_{11} - C_{12})/\rho]^{\frac{1}{2}} = 1.23 \times 10^6 \text{cm/sec},\\ v_z &= (C_{33}/\rho)^{\frac{1}{2}} = 3.92 \times 10^5 \text{cm/sec},\\ \sigma &= \text{Poisson ratio} = C_{12}/C_{11}, \;\; \varsigma = C_{44}/\rho. \end{aligned} \tag{2}$$

ς or C_{44} is very sensitive to crystal perfection, especially to the degree of stacking faults. The magnitude of C_{44} ranges from 10^{10}dynes/cm^2 to 10^9dynes/cm^2.[1]–[4] To solve Eq. 1, two limiting boundary conditions are imposed at $z = 0$ and $z = -d$, where d is the film thickness along the c–axis. Strain free and stress free conditions give rise to the same equations:

$$\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x} = 0, \;\; \frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y} = 0, \;\; \frac{\partial u_z}{\partial z} = 0, \tag{3}$$

at $z = 0$ and $z = -d$. Solution of Eq. 1 is obtained in the form:

$$\vec{u}(r) = \vec{U} e^{\kappa z} e^{i(qx - \omega t)} \tag{4}$$

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The general solution $\vec{u}(r) \propto e^{i(\vec{q}\cdot\vec{r}-\omega t)}$ can be obtained from Eq. 4 by rotating the coordinate axis in the xy–plane. Inserting Eq. 4 into Eq. 1, we obtain $u_y = 0$ and

$$\begin{aligned}(\omega^2 - v_\ell^2 q^2 + \varsigma\kappa^2)U_x + i\varsigma q\kappa U_z &= 0\\ i\varsigma q\kappa U_x + (\omega^2 - \varsigma q^2 + v_z^2\kappa^2)U_z &= 0.\end{aligned} \tag{5}$$

Two positive roots κ_1^2 and κ_2^2 exist, if the Rayleigh wave velocity $v_R = \omega/q$ satisfies the condition:

$$v_R^2 < \varsigma = C_{44}/\rho. \tag{6}$$

In terms of the phonon operators b_q^+ and b_q the energy of the Rayleigh wave is quantized according to

$$2\int d\vec{r} \quad \frac{\rho}{2}\left\{ \mid \frac{\partial \vec{u}_a}{\partial t} \mid^2 + \mid \frac{\partial \vec{u}_z}{\partial t} \mid^2 \right\} = \sum_q \hbar\omega_q (b_q^+ b_q + \frac{1}{2}), \tag{7}$$

where $\vec{u}_a = (u_x, u_y)$ and u_z are given by

$$\vec{u}_z \simeq \alpha\vec{n}\sum_q B_q[\beta_0 e^{\alpha q z} - \beta_0 e^{-\alpha q(z+d)} - \alpha cosh\beta qz - \frac{\alpha\beta_0}{\beta} sinh\beta qz] \times [b_q^+ e^{-i(qr-\omega t)} + b_q e^{i(qr-\omega t)}], \tag{8}$$

where $\vec{q} = (q_x, q_y)$, $\vec{n}$ is a unit vector along the z–axis and

$$\begin{aligned}&B_q \simeq \tfrac{1}{\alpha^2}\left(\tfrac{\hbar}{2\rho\omega_q\Omega}\right)^{\frac{1}{2}}, \quad \alpha \simeq v_\ell/\varsigma^{\frac{1}{2}} = 38.3, \quad \Omega = \text{sample volume},\\ &\beta_0 \simeq \varsigma^{\frac{3}{2}}/(v_\ell v_z^2) = 5.09\times 10^{-4}, \quad \beta \simeq \left(\tfrac{2\beta_0}{qd}\right)^{\frac{1}{2}},\\ &v_R^2 = \varsigma\left(1 - \tfrac{v_z^2\beta^2}{\varsigma}\right) \simeq \varsigma\left(1 - \tfrac{0.05}{qd}\right) \simeq \varsigma.\end{aligned} \tag{9}$$

The last relation in Eq. 9 is valid for $qd > 0.1$, which leads to $d > 10^{-7}$cm since $q \sim 10^6 cm^{-1}$. In Eq. 9 it is assumed that $\varsigma = 3.0\times 10^9 cm^2/sec^2$, a typical value for samples with a high degree of stacking faults.[2,4] It is easily shown that

$$\vec{u}_a << \vec{u}_z \simeq -\alpha^2\vec{n}\sum_q (cosh\beta qz + \frac{\beta_0}{\beta} sinh\beta qz)[b_q^+ e^{-i(qr-\omega t)} + b_q e^{i(qr-\omega t)}]. \tag{10}$$

For $d < 10^{-6}$cm, Eq. 10 represents a weakly damped Rayleigh wave with polarization along the c–axis.

ELECTRON–RAYLEIGH WAVE INTERACTION

The relaxation rate due to the scattering by the Rayleigh wave phonons is obtained as follows[5]:

$$1/\tau_R(E_k) \simeq \frac{2\pi k_0 T D^2}{\hbar\rho v_R^2 d^2\Omega}\sum_{k'}\frac{1}{q^2}\left(1 - \frac{k'_z}{k_z}\right)\delta(E_k - E_{k'}), \tag{11}$$

where $\vec{q} = \vec{k}'_a - \vec{k}_a$, and $\vec{k}_a = (k_x, k_y)$. In deriving Eq. 11, the high temperature approximation $N_q \sim N_q + 1 \sim k_0T/\hbar\omega_q$ is employed, since $\hbar\omega_q/k_0 < 1K$ for $q \sim 10^6\text{cm}^{-1}$. D is the electron–phonon coupling constant associated with the out–of–plane vibration and in bulk graphite D = 3.7 eV.[6] From Eq. 11, we then obtain

$$\frac{1}{\tau_R} \simeq \frac{k_0 T}{2\pi\hbar^2\rho c_0}\frac{L_a}{v_F}\left(\frac{D}{v_R d}\right)^2 \simeq 4\times 10^{11} T/secK, \tag{12}$$

where L_a denotes the dimension of the thin film in the basal–plane. In evaluating Eq. 12, the following parameters are employed:

$$v_R = 4.5 \times 10^4 \mathrm{cm/sec}, \quad d = 70\text{Å}, \quad L_a = 100\text{Å}, \quad v_F = 2 \times 10^7 \mathrm{cm/sec}. \qquad (13)$$

The electron–Rayleigh wave interaction is responsible for the anomalous temperature dependent negative magnetoresistance of pregraphitic carbons at low temperatures.[7]

CONCLUSIONS

1. Sound wave propagation in this film carbon is investigated in the long wavelength approximation. If the sample thickness d is small ($<$ 100 Å) the Rayleigh wave with a small sound velocity ($\sim 10^4$ cm/sec) propagates without damping and this wave is polarized along the c–axis.
2. Carriers are strongly scattered by the phonons associated with the Rayleigh wave even at $T \leq 1$K, since the typical phonon energies interacting with carriers are at most 1K.
3. Though the carrier relaxation rate relative to the interaction with the Rayleigh wave phonons is one order smaller than that for the impurity scattering, it plays an important role in the negative magnetoresistance of disordered carbons at low temperature.[7]

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